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A Selection Method for Restoration Mortars Using Sustainability and Compatibility Criteria

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Table S1. Colour of Mortars in green the mortars with less than 10 and in blue commercial mortars.

	Sample	L	a	b	ΔE Lutetian	ΔE Oxpemul	ΔE Euville	ΔE Mayapan	ΔE Dzibichaltun	ΔE Chichen Itzá	ΔE Calakmul
1	**HFD**	74.52	2.63	10.04	9.2	2.3	14.0	8.8	3.6	4.0	2.9
2	**HSD**	74.14	2.72	11.52	8.1	1.1	14.8	8.5	2.5	3.2	2.0
3	**HS**	72.88	2.55	9.93	10.2	3.1	15.6	7.2	4.4	5.2	1.9
4	**HB**	62.85	10.71	11.47	18.8	14.7	27.3	8.4	14.3	15.9	12.1
5	**HCSR**	84.17	1.41	5.95	13.4	11.3	4.1	19.1	11.7	10.5	13.4
6	**HCS**	81.1	1.83	7.954	10.5	7.6	7.1	15.7	8.1	7.0	9.8
7	**HSG**	82.19	1.44	6.19	12.6	9.6	6.0	17.1	10.1	9.1	11.5
8	**HSP**	82.66	1.64	8.46	10.5	8.7	5.7	17.1	9.0	7.7	11.1
9	**HC**	82.19	2.12	9.11	9.7	8.0	6.4	16.6	8.2	6.9	10.4
10	**HCSGB**	81.74	3.19	9.13	9.4	7.7	7.0	16.1	7.6	6.4	9.9
11	**AS**	87.55	1.18	7.55	13.9	13.6	1.0	22.1	13.7	12.3	16.0
12	**AHCS**	83.09	1.69	8.7	10.5	9.0	5.4	17.5	9.2	7.9	11.4
13	**ACSGB**	87.05	2.38	5.93	14.7	13.8	1.6	21.9	13.8	12.6	16.0
14	**OAC ***	84.49	1.74	8.55	11.2	10.4	4.0	18.9	10.5	9.1	12.8
15	**AC**	86.53	1.81	8.35	12.5	12.4	2.2	21.0	12.3	11.0	14.8
16	**AS2**	81.32	1.16	7.26	11.4	8.3	6.8	16.1	8.9	7.8	10.3
17	**H3.5CS**	84.21	2.22	9.79	10.0	9.7	4.9	18.5	9.6	8.2	12.2
18	**H3.5CS2**	86.84	1.78	8.84	12.4	12.5	2.4	21.2	12.5	11.1	15.0
19	**H3.5CS3**	87.94	1.25	7.42	14.2	14.0	0.7	22.5	14.1	12.7	16.4
20	**H3.5CS4**	85.96	1.73	7.89	12.6	12.0	2.4	20.5	12.0	10.7	14.4
21	**H3.5CS5**	87.65	1.31	7.22	14.2	13.8	0.7	22.3	13.9	12.6	16.2
22	**H3.5CSG**	84.94	1.82	10.04	10.3	10.4	4.5	19.3	10.3	8.9	12.9
23	**H3.5CSB**	83.28	3.43	9.76	9.5	8.9	5.9	17.6	8.6	7.4	11.3
24	**H3.5CSGB**	79.02	4.72	12.68	5.6	4.9	11.2	13.6	3.7	2.7	7.2
25	**Lithomex**	79.5	2.31	11.23	7.0	4.8	9.7	13.8	4.9	3.5	7.4
26	**Artropierre**	88.04	0.81	6.37	15.2	14.6	1.0	22.8	14.7	13.4	16.9
27	**Altar Pierre**	75.64	1.94	10.39	8.5	2.1	13.0	10.0	3.5	3.4	3.8
28	**Lutetian stone**	78.84	3.43	18.12	0.0	7.2	14.7	15.2	6.0	5.3	9.3
29	**Oxpemul**	74.81	2.21	12.28	7.2	0.0	14.4	9.3	2.1	2.5	2.8
30	**Euville stone**	88.14	1.64	6.86	14.7	14.4	0.0	22.8	14.4	13.1	16.7
31	**Mayapan**	65.7	2.87	10.6	15.15	9.29	22.78	0.0	10.1	11.4	6.6
32	**Dzibichaltun**	75.4	4.06	13.2	6.04	2.15	14.43	10.1	0.0	1.6	3.8
33	**Chichen Itzá**	76.8	3.305	13.23	5.30	2.46	13.11	11.42	1.59	0.0	4.9
34	**Calakmul**	72.16	2.91	11.7	9.28	2.80	16.75	6.55	3.75	4.9	0.0

Table S2. Physical and mechanical properties of limestones. **ϱ**: density **(**kg/m³**)**, **n**: open porosity (%), **C**: Capillarity coefficient **(**Kg/m²s½**)**, **S**: Compressive Strength (MPa) standard deviation (SD), the values for mayan stones are taken from Che-Novelo[69] and the values for commercial mortars from Tangith-Hammou [70] and Lopez-Arce .[12]

Mortar	ϱ	SD ϱ	ø	SD ø	C	SD C C	S 180	SD S-180
Lutetian stone	1617	19	37	0.8	0.35	0.04	8.5	0.83
Euville stone	1943	48	19	1.4	0.46	0.02	8.6	1.2
Mayapan	-	-	-	-	-	-	-	-
Dzibichaltun	2310	12	12	0.5	0.46	0.06	8	0.6
Chichen Itzá	-	-	-	-	-	-	-	-
Calakmul	1970	60	25	2	0.3	0.03	4.31	0.7
Oxpemul	1520	173	42	6.63	0.55	0.06	12.5	0.7

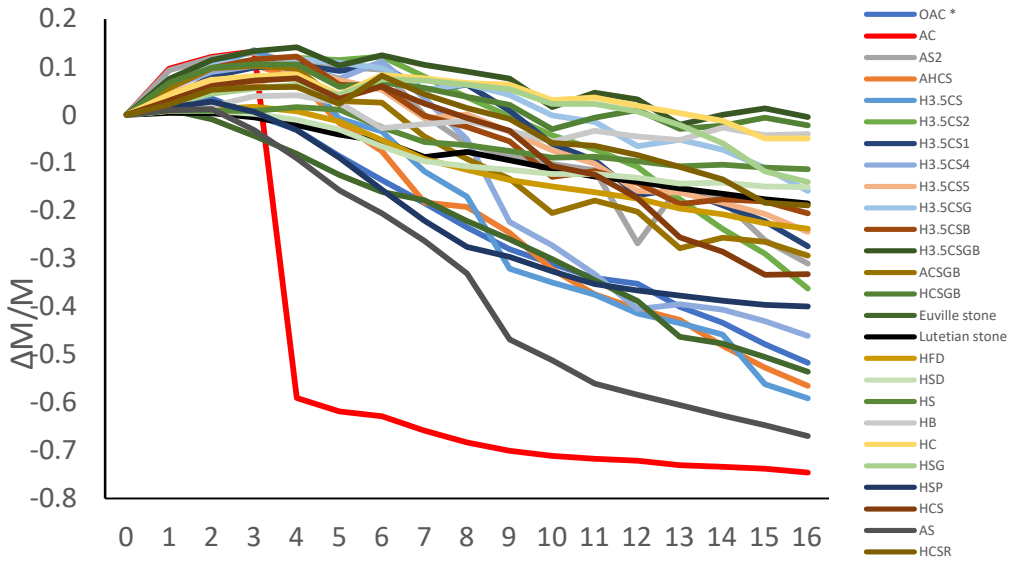

Figure S1. Durability of restoration mortars in salt crystallization test.

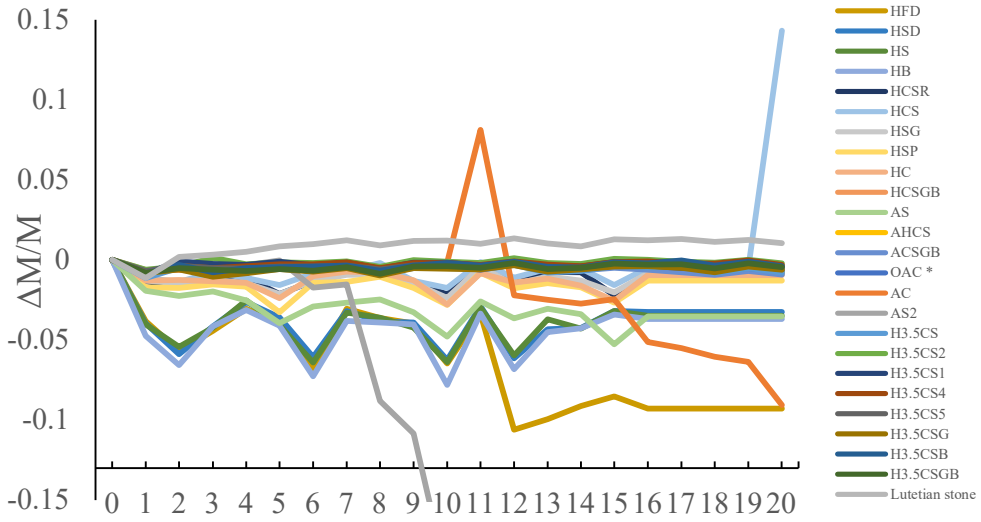

Figure S2. Durability of restoration mortars in freezing thawing test.

Table S3. Mass difference in the Durability of restoration mortars after the last cyle.

Mortar Formulation	ΔM/M Salt Crystallization	ΔM/M Freezing Thawing
	Cycle 16	Cycle 20
HFD	-0.24	-0.04
HSD	-0.15	-0.03
HS	-0.11	-0.03
HB	-0.04	-0.04
HSCR	-0.19	-0.01
HCS	-0.33	0.14
HSG	-0.14	-0.01
HSP	-0.40	-0.01
HC	-0.05	-0.01
HCSGB	-0.02	0.00
AS	-0.67	-0.04
AHCS	-0.56	-0.01
ACSGB	-0.29	-0.01
OAC *	-0.52	-0.01
AC	-0.75	-0.09
AS2	-0.31	-0.56
H3.5CS	-0.59	-0.01
H3.5CS2	-0.36	0.00
H3.5CS3	-0.27	0.00
H3.5CS4	-0.46	0.00
H3.5CS5	-0.24	-0.01
H3.5CSG	-0.16	-0.01
H3.5CSB	-0.21	0.00
H3.5CSGB	0.00	0.00

Using equation 4, Table 3 and Table 8

$GWP\ (\text{kg}\ \text{CO}_{2\ \text{eq}}/\text{t}) = \sum M_i EF_i$

(2)

The composition of the mortar and the distance, calculation for HFD mortar is as follows

$Row\ materials\ GWP\ \left(\text{kg}\frac{\text{CO}_{2\ \text{eq}}}{\text{t}}\right) = 200 * 0.74 + 200 * 0.07 + 600 * 0.05 = 192\ kg\ \text{CO}_{2\ \text{eq}}$

For the transport we use the calculated distance in Table 8

$Transport\ and\ Disposal\ GWP\ \left(\text{kg}\frac{\text{CO}_{2\ \text{eq}}}{\text{t}}\right) = 0.2 * 790 * 0.368 + 0.2 * 90 * 0.368 + 0.6 * 55 * 0.368 + 1 * 65 * 0.368 = 101\ kg\ \text{CO}_{2\ \text{eq}}$ giving a total of $\mathbf{293\ \ kg\ CO_{2\ eq}/t}$

Table S4. Emission factors of inputs [49.]

Inputs	Unit	*EF*
Portland Cement	kg CO_2 eq/kg	1.53
CL90	kg CO_2 eq/kg	0.98
NHL5	kg CO_2 eq/kg	0.74
NHL3.5	kg CO_2 eq/kg	0.64
Silica Sand	kg CO_2 eq/kg	0.045
Calcareous Sand	kg CO_2 eq/kg	0.03
Silico-Calcareous Sand	kg CO_2 eq/kg	0.05
Fine Silica Sand	kg CO_2 eq/kg	0.07
Transport (raw materials)	kg CO_2 eq/tkm	0.368
Transport (disposal)	kg CO_2 eq/tkm	0.368

Table S5. LCA calculation of a restoration mortar.

	Mortar Formulations in Kg					
Raw material	**1(HFD)**	**2(HSD)**	**9(HC)**	**17(HCSGB)**	**23(H3.5CSB)**	**24(H3.5CSGB)**
NHl5	200	200	300	300		
NHl3.5					300	300
Sand F	200	150				
Sand S		650		250	300	250
Sand C			700	250	300	250
Sand D	600					
G				100		100
B				100	100	100
Row materials	192	188	243	241	215	211
Transport and Disposal	101	136	128	136	141	136
TOTAL	293	324	371	377	355	347

Table S6. Additives normally use in mortars.

Additive	**Properties**	**Reference**
Plasticizers	Lignosulfonates and Polycarboxylates are powerful water reducers, likewise plasticize or fluidize. They are used in special mortars, tile joint fillers, cement plates, plasterboards, and in general they can be used where it is required to achieve high mechanical properties without the need for vibration	[71]
Waterproofing	Water repellents based on the chemical sodium oleate is ideal for Stucco that must be used as protection against water. Effect is almost immediate, 7 days after application. Water permeability reducer, for stuccoes and cementitious nozzles where it is required to protect against water absorption Immediate and durable effect for 2-3 years.	[72]
Cellulose	HPMC and HEMC cellulose ethers are usually used to maintain water content in mortars at high levels. These molecules also contribute to good mechanical strength of the final material.	[73]
Organic additions	Different organics additions in the lime matrix have demonstrated enhances the mechanical properties of the mortar significantly as it improves the binding strength between two consecutive lime particles in the mortar.	[74–78]
Acrylate resin powder	It contributes to increase mechanical properties of adherence, flexibility, modulus of elasticity, impact resistance and hardness. It is ideal for protection against UV rays, and high resistance to humidity.	[79,80]
Starch	Highly substituted natural polysaccharide, designed to improved functional properties including: solution stability, salt tolerance, area of activity, water retention, viscosity and improved its rheology.	[81]
Fibers	The fibers are used to obtain better consistency control, It increases flexibility and adherence, it does not affect the water-cement ratio. The polyester fiber continues working once the mortar has set and hardened.	[82,83]
Dispersants	Naphthalene sulfonate, a high molecular weight dispersant for the dispersion of cement. Water reducer for mortars.	[84–87]
Anti-foaming	White cellulose fiber ideal for ceramic adhesives and stucco, increases open time and drying time. It reduces the sagging of the putties and the formation of cracks.	[88]
Pigments	Material that changes the colour of the light that is reflected or transmits as a result of the selective light absorption according to its wavelength.	[89,90]
Pozzolans and mineral additions	The use of waste materials to fill the role of an aggregate filler or pozzolan have grown in importance in recent years, as have metakaolin, ground glass and clays. Increasing mechanical properties of lime-based mortars.	[67,91,92]
Nanoparticles	Many nanosized products have been tested in the construction industry such as, nanosilica (SiO_2,) nanotitania (TiO_2) cellulose nanofibers ($(C_6H_{10}O_5)_n$) and nanolime ($Ca(OH)_2$). Nanoparticles have very high specific surface area and their properties and effects on physical properties and chemical reactions may vary from those of the same materials with micro/millimetric dimensions.	[71,82,93–96]

Latex resin	Natural and synthetic latex have been used successfully in order to produce proprietary mortars, screeds and surface coatings. These are often used to produce chemically resistant floor toppings, styrene butadiene latex is used to improve bonding in many substrates and other polymeric resins, such as acrylic polymers, polyvinyl acetate and epoxy resins.

Table S7. XRAY composition of raw materials and admixtures.

Formula	Compound Name	NHl5	CL90	Sand D	Sand F	Sand S	Sand C	B	G
Si O2	Quartz	6.70%		96.80%	82.00%	88.80%	7.20%	67.60%	99.00%
Ca C O3	Calcite	30.00%	11.60%		14.70%	4.50%	89.50%		0.50%
Ca C O3	Aragonite						1.40%		
Ca (O H)2	Portlandite	14.10%	88.40%						0.50%
Ca3 Si O5	Alite	17.50%							
Ca2 Si O4	Belite/ Larnite	12.80%							
K2 Ca6 Si4 O15	Potassium Calcium Silicate	7.30%							
Ca2 Al2 Si O7	Gehlenite	7.20%							
Ca2 Mg0.05 Fe0.95 Al0.95 Si0.05 O5	Brownmillerite	4.40%							
(Na0.7K0.3)(Al1.02Si2.98O8)	Albita potassian			3.20%	3.30%			7.20%	
Na(AlSi3O8)	albite sodium					2.50%			
CaAl2Si2O8	Anorthite ordered					4.20%		12.30%	
CaAl2Si7O187.5H20	heulandite							6.80%	
Fe2O3	hematite							1.90%	
Al3.2 Ca3.4 Fe4 K0.6 Mg6 Na Si12.8 O44 (O H)4	amphibiole							2.50%	
Na2 Fe3 Fe2 Si8 O22 (O H)2	Riebeckite							1.70%	
Ca Mg0.46 Fe0.54 (C O3)2	Ankerite, magnesian						1.90%		

Table S8. Distance of the raw materials for Mayan monuments.

Raw Material	Company	Factory location	Distance to Dzibichaltun (Km)
Air Lime	Productora de cal de Yucatán	Km. 6 Carretera Mérida-Cholul, Yucatán, 97300	14
Hydraulic Lime	Granding International	Exuberancia 10, La Esmeralda, Jiutepec, Morelos, 62555	1347
Calcareous Sand	MAPSA	Anillo periferico sur km 8, Mérida, Yucatán 97300	37
Silica Sand	Arena Silica del Golfo	Carretera Fenquimia km 01-80, Cosoleacaque, Veracruz, 9634	760
Silica-Calcareous Sand	mix MAPSA and Arena silica del Golfo	mix CP: 97300 and 9634	616
Silica -Fine Sand	Arena Silica del Golfo	Carretera Fenquimia km 01-80, Cosoleacaque, Veracruz, 9634	760
Raw Material	**Company**	**Factory Location**	**Distance to Calakmul (Km)**
Air Lime	Productora de cal de Yucatán	Km. 6 Carretera Mérida-Cholul, Yucatán, 97300	458
Hydraulic Lime	Granding International	Exuberancia 10, La Esmeralda, Jiutepec, Morelos, 62555	1200
Calcareous Sand	MAPSA	Anillo periferico sur km 8, Mérida, Yucatán 97300	439
Silica Sand	Arena Silica del Golfo	Arena Silica del Golfo	612
Silica-Calcareous Sand	mix MAPSA and Arena silica del Golfo	mix CP: 97300 and 9634	578
Silica -Fine Sand	Arena Silica del Golfo	Carretera Fenquimia km 01-80, Cosoleacaque, Veracruz, 9634	612
Raw Material	**Company**	**Factory Location**	**Distance to Oxpemul (Km)**
Air Lime	Productora de cal de Yucatán	Km. 6 Carretera Mérida-Cholul, Yucatán, 97300	488
Hydraulic Lime	Granding International	Exuberancia 10, La Esmeralda, Jiutepec, Morelos, 62555	1230
Calcareous Sand	MAPSA	Anillo periferico sur km 8, Mérida, Yucatán 97300	470
Silica Sand	Arena Silica del Golfo	Carretera Fenquimia km 01-80, Cosoleacaque, Veracruz, 9634	643
Silica-Calcareous Sand	mix MAPSA and Arena silica del Golfo	mix CP: 97300 and 9634	609
Silica -Fine Sand	Arena Silica del Golfo	Carretera Fenquimia km 01-80, Cosoleacaque, Veracruz, 9634	643

Table S9. LCA of mortars for Different sites.

		kg CO2 eq/t			
#	Mortar	Dzibichaltun	Calakmul	Oxpemul	Palais Royal
1	**HFD**	497	615	637	294
2	**HSD**	524	618	641	324
3	**HS**	520	614	637	273
4	**HB**	261	398	411	240
5	**HCSR**	541	686	708	394
6	**HCS**	541	686	708	394
7	**HSG**	579	678	700	405
8	**HSP**	605	700	722	415
9	**HC**	415	650	673	371
10	**HCSGB**	476	631	652	377
11	**AS**	469	574	594	360
12	**AHCS**	475	647	668	419
13	**ACSGB**	400	571	588	427
14	**OAC ***	432	668	687	535
15	**AC**	432	668	687	535
16	**AS2**	600	716	734	575
17	**H3.5CS**	476	631	652	346
18	**H3.5CS2**	444	637	659	355
19	**H3.5CS3**	483	648	670	364
20	**H3.5CS4**	523	659	681	373
21	**H3.5CS5**	562	670	692	383
22	**H3.5CSG**	465	625	646	355
23	**H3.5CSB**	465	625	646	355
24	**H3.5CSGB**	446	601	622	347

Table S10. Assignment of values in restoration mortars for Dzibichaltun stone.

#	Mortar	Co	CA	CS	D1	D2	DE	PO	GW	P	Score
1	**HFD**	64	97	43	76	98	56	82	50	82	648
2	**HSD**	75	94	42	85	92	50	82	48	81	648
3	**HS**	56	97	37	89	92	56	82	48	81	638
4	**HB**	0	87	41	96	85	31	72	74	87	572
5	**HCSR**	0	100	61	81	86	52	78	46	76	580
6	**HCS**	0	86	57	67	86	54	79	46	76	550
7	**HSG**	0	88	103	86	89	64	83	42	76	630
8	**HSP**	10	87	27	60	85	36	74	40	75	494
9	**HC**	18	95	67	95	87	46	76	59	77	619
10	**HCSGB**	24	84	95	98	91	39	78	52	77	638
11	**AS**	0	96	34	33	91	52	79	53	74	512
12	**AHCS**	8	91	40	44	86	48	76	53	71	516
13	**ACSGB**	0	87	35	71	82	26	75	60	66	502
14	**OAC ***	0	86	36	48	82	34	72	57	57	472
15	**AC**	0	77	40	25	87	20	67	57	57	429
16	**AS2**	11	82	30	69	54	28	70	40	56	439
17	**H3.5CS**	4	82	46	41	82	38	72	52	77	493
18	**H3.5CS2**	0	82	42	64	81	36	71	56	77	508
19	**H3.5CS3**	0	92	50	73	84	43	75	52	74	543
20	**H3.5CS4**	0	85	39	54	84	43	75	48	74	501
21	**H3.5CS5**	0	88	42	76	85	47	76	44	73	530
22	**H3.5CSG**	0	97	54	84	84	37	78	54	73	560
23	**H3.5CSB**	14	98	55	79	84	38	77	54	74	573
24	**H3.5CSGB**	63	96	68	100	84	34	75	55	75	650
25	**Lithomex**	51	76	90	85	85	36	80	50	38	591
26	**Artropierre**	0	88	90	85	85	26	73	50	38	535
27	**Altapierre**	65	95	0	85	85	57	87	50	38	562

Table S11. Assignment of values in restoration mortars for Calakmul.

#	Mortar	Co	CA	CS	D1	PO	GW	P	Score
1	HFD	71	97	80	76	95	39	82	539
2	HSD	80	94	79	85	95	38	81	552
3	HS	81	97	74	89	95	39	81	555
4	HB	0	87	78	96	85	60	87	493
5	HCSR	0	100	98	81	91	31	76	477
6	HCS	2	86	94	67	92	31	76	448
7	HSG	0	88	140	86	96	32	76	518
8	HSP	0	87	64	60	87	30	75	403
9	HC	0	95	104	95	89	35	77	495
10	HCSGB	1	84	132	98	91	37	77	520
11	AS	0	96	71	33	92	43	74	409
12	AHCS	0	91	77	44	89	35	71	407
13	ACSGB	0	87	72	71	88	43	66	426
14	OAC *	0	86	73	48	85	33	57	382
15	AC	0	77	77	25	80	33	57	349
16	AS2	0	82	67	69	83	28	56	385
17	H3.5CS	0	82	82	41	85	37	77	404
18	H3.5CS2	0	82	79	64	84	36	77	422
19	H3.5CS3	0	92	87	73	88	35	74	449
20	H3.5CS4	0	85	76	54	88	34	74	410
21	H3.5CS5	0	88	78	76	89	33	73	438
22	H3.5CSG	0	97	91	84	91	38	73	473
23	H3.5CSB	0	98	92	79	90	38	74	471
24	H3.5CSGB	28	96	105	100	88	40	75	532
25	Lithomex	26	76	127	85	93	50	38	494
26	Artropierre	0	88	127	85	86	50	38	473
27	Altapierre	62	95	0	85	100	50	38	430

Table S12. Assignment of values in restoration mortars for Oxpemul stones.

#	Mortar	Co	CA	CS	D1	D2	DE	PO	GW	P	Score
1	**HFD**	77	97	0	76	98	65	88	36	82	619
2	**HSD**	89	94	0	85	92	71	88	36	81	636
3	**HS**	69	97	0	89	92	65	88	36	81	617
4	**HB**	0	87	0	96	85	90	98	59	87	602
5	**HCSR**	0	100	16	81	86	69	92	29	76	549
6	**HCS**	24	86	12	67	86	67	91	29	76	538
7	**HSG**	3.4	88	58	86	89	57	87	30	76	574
8	**HSP**	13	87	0	60	85	85	96	28	75	529
9	**HC**	20	95	22	95	87	75	94	33	77	597
10	**HCSGB**	23	84	50	98	91	83	92	35	77	632
11	**AS**	0	96	0	33	91	69	91	41	74	495
12	**AHCS**	10	91	0	44	86	73	94	33	71	502
13	**ACSGB**	0	87	0	71	82	95	95	41	66	537
14	**OAC ***	0	86	0	48	82	87	98	31	57	489
15	**AC**	0	77	0	25	87	99	97	31	57	473
16	**AS2**	17	82	0	69	54	93	100	27	56	498
17	**H3.5CS**	3	82	1	41	82	83	98	35	77	501
18	**H3.5CS2**	0	82	0	64	81	85	99	34	77	522
19	**H3.5CS3**	0	92	5	73	84	78	95	33	74	534
20	**H3.5CS4**	0	85	0	54	84	78	95	32	74	501
21	**H3.5CS5**	0	88	0	76	85	74	94	31	73	521
22	**H3.5CSG**	0	97	9	84	84	85	92	35	73	559
23	**H3.5CSB**	11	98	10	79	84	83	93	35	74	568
24	**H3.5CSGB**	51	96	23	100	84	87	95	38	75	649
25	**Lithomex**	52	76	45	85	85	85	90	50	38	606
26	**Artropierre**	0	88	45	85	85	95	97	50	38	582
27	**Altapierre**	79	95	0	85	85	64	83	50	38	579

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